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UNDERWATER CYCLE ERGOMETRY: POWER REQUIREMENTS WITH AND WITHOUT DIVER THERMAL DRESS

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19. ABSTRACT: Navy Experimental Diving Unit (NEDU) uses cycle ergometers to increase diver oxygen consumption in many different experiments. An ongoing problem has been that, although the power requirement of cycling in the water is known to be greater than that in air for the same ergometer setting, the magnitude of the difference, particularly with diver thermal dress, has been unclear. We compared oxygen consumption during dry ergometry to that during ergometry in head-out water immersion among a total of 25 cycling subjects who wore PT gear, wet suits, dry suits, or non-return valve (NRV) suits. We also measured the effects of pedal cadence with different diver dress. Additional power varied greatly among subjects and was either independent of ergometer setting or increased with setting. Mean additional power when constant with increased ergometer setting was 64 (standard error [SE] 5) W, 69 (SE 5) W, 104 (SE 9) W, and 126 (SE 7) W at 60 rpm in PT gear, wet suit, dry suit, and NRV suit, respectively. Additional power requirements varied approximately with the cube of cadence, a variation suggesting drag and moment of inertia, not additional torque, as the causes. Additional power in a wet suit was no different from that in PT gear. Greater pedal drag and less stable subject position may cause a greater additional power requirement at NEDU than that measured at other institutions. High intersubject variations mean that a direct measure of oxygen consumption is necessary, if that variable must be controlled.

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INTRODUCTION

Underwater cycle ergometers allow divers, even if tethered to instrumentation, to increase oxygen consumption in the confines of a test pool or wet hyperbaric chamber. However, the power output of a diver is greater than that transmitted to the pedals of the ergometer, because energy is consumed by water resistance and potentially by flexion of thermal protection suits. Oxygen consumption for cycle ergometry power settings in air thus underrepresents that in the water at similar settings; for water immersion alone, one report lists an offset of 50 W,[1] and two others found 25 W.[2,3] Navy Experimental Diving Unit (NEDU) uses cycle ergometers extensively during in-water work, work that would be enhanced by a clearer knowledge of the oxygen consumption range for any particular ergometer setting.

We measured oxygen consumptions while subjects pedaled an underwater cycle ergometer at incrementally increased power settings. Because the additional loads of in-water pedaling are independent of head immersion, our subjects cycled with their heads out of the water, a position enabling us to measure oxygen consumption breath by breath. We also measured oxygen consumption for the same subjects during incremental tests on a dry ergometer similar to the in-water one. Those measurements were used to compute the relation between the individual's oxygen consumption and his or her leg power. We used that relation in conjunction with the measured in-water oxygen consumptions and the known power setting of the ergometer to compute the effective additional power load caused by the water. Measurements in the water were made while subjects wore shorts and T-shirts ("wet PT gear"), wet suits, dry suits, and non-return valve (NRV) tube suits. We also measured the effects of pedal cadence on power requirements in the water when the ergometer was adjusted to require constant power output independent of cadence.

METHODS

GENERAL

Three cycle ergometers were carefully characterized to provide known loads at given constant brake current. In brief, the brakes were mounted in gear boxes and the gear boxes mounted on the test bench. A constant speed motor (Minarik Electric; Los Angeles, CA) with reducing gears was used to turn the pedal shaft of the gear box and thus to spin the rotor of the brake. A shaft torque meter (Torquemaster TM211, Magtrol; Buffalo, NY) interposed between the driving motor and the pedal shaft gave a continuous readout, and electrical current was applied to the brake from a constant-current power supply (Magtrol 5210, Magtrol; Buffalo, NY). Current was increased incrementally until the torque reached about 40 Newton meters (Nm), corresponding to 250 W at 60 revolutions per minute (rpm); at higher currents, the brakes began to overheat. Current was run up and down at least three times, and an average current–

shaft power curve was recorded for increasing current. We used only increasing currents throughout testing because of the brake hysteresis; when a decrease in shaft power was needed, we reduced the current to zero and then increased it to the required value.

One pedal box was characterized with its case open. It was then mounted in an upright cycle ergometer frame to make the dry ergometer. Two others were characterized with their cases sealed, and one was mounted in an underwater ergometer frame of the type generally used at NEDU. These frames provide semiprone cycling in the water to mimic a swimming posture. There is no seat, but users brace themselves between the pedals and a pair of curved shoulder horns. They slide their feet into a pair of foot cups cut from dive fins (Turtle fins, XXL) and bolted to the pedals. The shoulder horn to pedal box distance is adjusted by sliding the horns.

The protocol for this study was approved by NEDU's Institutional Review Board. Twenty-five subjects, 20 men and five women, were recruited from NEDU, surrounding commands, and NEDU Reserve Unit Great Lakes. All subjects gave written informed consent and underwent medical screenings before beginning the study.

Each subject completed an incremental exercise test on the dry ergometer and one or more incremental tests in the water with different thermal protection garments. Most subjects performed a test of the effects of pedal cadence instead of an incremental test with one form of diver dress, but five subjects underwent no cadence test, and six subjects completed an extra cadence test. The goal was for each subject to be tested with each form of diver dress, but time constraints meant that some were unable to complete the series (Table 1).

Each incremental test continued until the subject could not maintain cadence or chose to stop. Although 30 seconds in the water with heart rate at or above the peak seen in dry testing was a termination criterion, no incidences occurred during testing. During the tests of cadence effects, the ergometer was set to no added load (10 W at 60 rpm), 30 W, or 50 W, and subjects pedaled at 45, 60, or 75 rpm while oxygen consumption was measured.

EXPERIMENTAL DESIGN AND ANALYSIS

Subjects warmed up for four minutes without additional load on the ergometer, after which each power level was maintained for three minutes to reach steady state. Oxygen consumption and related variables were recorded breath by breath during testing, and the values ascribed to the exercise level were the averages over the last minute at that level. When subjects could not complete three minutes at their highest power increments, data from those increments were used only if a steady state in oxygen consumption appeared to have been reached.

Table 1.

Subject characteristics

n total = 25 (20 men, 5 women)

Incremental Exercise, 60 rpm	n men	n women	Median (min – max)		
			Age [yr]	Height [in]	Weight [lb]
PT gear	17	3	37.5 (27–47)	69.5 (63–75)	191 (126–250)
Wet suit	15	3	35.5 (27–47)	69 (61–75)	182.5 (126–240)
Dry suit	13	1	37 (27–47)	69.5 (61–75)	185 (160–235)
NRV suit	9	5	36 (26–46)	68.5 (61–75)	186 (126–250)

Cadence	n men	n women	Median (min – max)		
			Age [yr]	Height [in]	Weight [lb]
PT gear	6	1	32.5 (27–40)	69.5 (66–75)	198.5 (165–215)
Wet suit	5	1	37.5 (34–46)	69 (67–72)	201 (136–250)
Dry suit	3	2	37 (27–40)	69 (63–74)	200 (126–240)
NRV suit	6	0	36 (29–47)	69.5 (66–75)	185 (165–235)

Regression equations for oxygen consumption as a function of power output on the dry bike were calculated for each subject, and the reciprocal of the dry relation was used to determine equivalent power output in the water from measured oxygen consumption ($V'O_2$). Confidence intervals on the power estimate were found from the confidence on the dry regression parameters.

For example, for the subject whose data are presented in Fig. 1, the regression line shown for dry oxygen consumption as a function of ergometer power was

$$V'O_2\ [\mathrm{mL} \cdot \mathrm{min}^{-1}] = 12 \cdot (\text{Shaft power [W]}) + 513, \qquad r^2 = 0.99.$$

The lower 95% confidence limits for slope and intercept were 11 mL · (min · W)$^{-1}$ and 396 mL · min^{-1}, respectively; upper limits were 16 mL · (min · W)$^{-1}$ and 630 mL · min^{-1}, respectively.

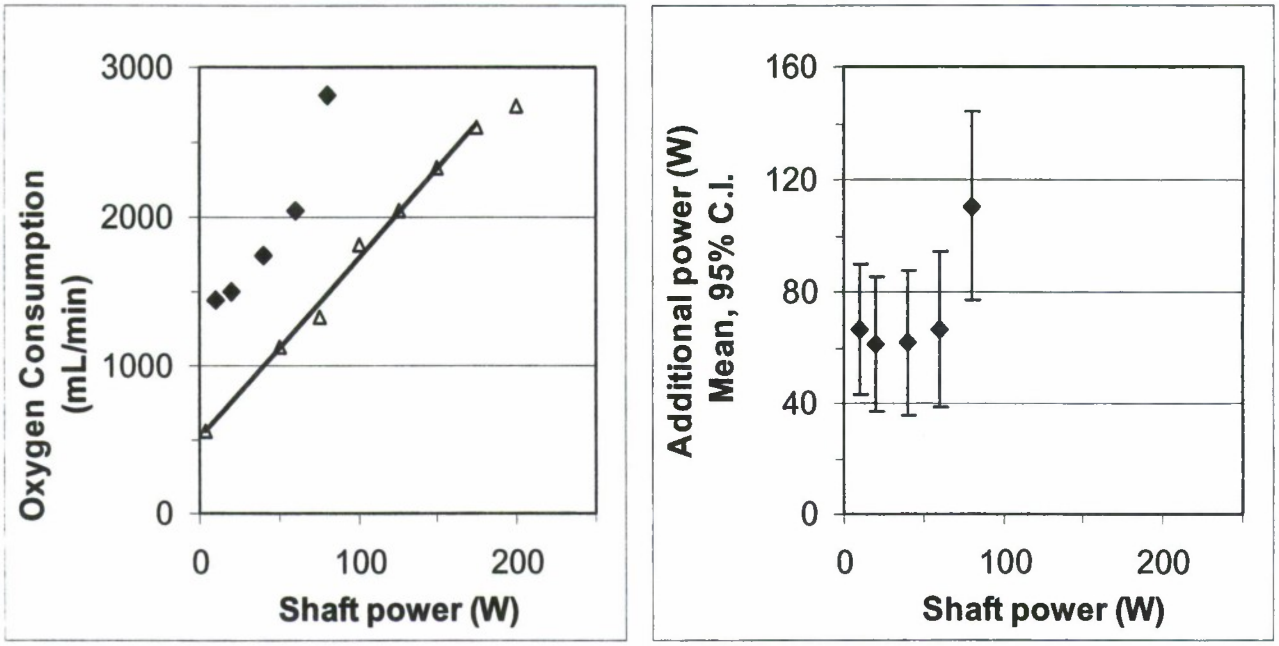

Figure 1. Calculation of additional power for one subject, wet PT gear. Solid diamonds: wet PT gear. Open triangles and regression line: dry ergometer. Vertical bars: 95% confidence intervals.

The regression line for oxygen consumption as a function of ergometer power correctly attributes most random error to the measurement of oxygen consumption. To convert from oxygen consumption to power, rather than compute the regression of power vs. oxygen consumption (a computation which assumes that oxygen consumption is error-free and that the random error is on the power setting), the inverse relation was used:

$$\text{Power [W]} = 0.083\ [\text{mL} \cdot \text{min}^{-1}]^{-1} \cdot V'O_2 - 42\ [\text{W}].$$

From the bounds on slopes and intercept, the lower 95% confidence bound on power was

$$\text{Power [W]} = 0.076\ [\text{mL} \cdot \text{min}^{-1}]^{-1} \cdot V'O_2 - 56\ [\text{W}],$$

and the upper bound was

$$\text{Power [W]} = 0.090\ [\text{mL} \cdot \text{min}^{-1}]^{-1} \cdot V'O_2 - 30\ [\text{W}].$$

These relations were applied at each of the measured oxygen consumptions shown in the first panel of Fig. 1 to yield the equivalent shaft power. As shown in the second panel of Figure 1, the additional power requirement of cycling in the water was the difference between equivalent power and the shaft power set for the ergometer, the value shown on the abscissa. Cadence results were analyzed similarly.

Average values of additional power were taken across ergometer settings when the calculated additional power appeared independent of ergometer setting, 10 W through 60 W in this example.

EQUIPMENT AND INSTRUMENTATION

The cycle ergometers were built at NEDU as successors to the waterproofed Collins Pedal Mate ergometers that are no longer available. A pedal shaft drives the shaft of a hysteresis brake (HB210, Magtrol; Buffalo, NY) through a gear train with an overall gear ratio of 1:19.2. The torque necessary to turn the brake is regulated by the electric current supplied to the brake. Because of hysteresis in the brake rotor (in addition to that which causes braking), torque is higher at a given setting if the current was decreased to the value than if it was increased. The ergometers thus were characterized and used only with increasing currents. Additionally, the same power supply used in characterizing the ergometer, a constant (regulated) current power supply, was used to provide a stable load: with a constant voltage supply, heating of the brake might have reduced current and changed torque.

Power (P) is related to Torque (T) as $P = T \cdot \omega$, where ω is rotational speed in radians/time. Thus, when rotational speed (cadence) increases, more power is required if torque is held constant. Since the cadences we wanted were 45, 60, and 75 rpm and we wanted to set the power (wattage), the ergometers were characterized at each of those rotational speeds. During use, the current was set manually for the desired power output at the target cadence. Subjects could see their pedal cadence on an analog meter connected to an electronic pickup. They also were offered an audible metronome tone to follow.

We measured oxygen consumption breath by breath during exercise using the COSMED k2b4 (Cosmed USA; Chicago, IL). Other investigators have published validation studies of the system against other metabolic carts.[4–6] Although small differences were seen between systems in all tests, correlations were tight, and test-retest reliability of the COSMED was satisfactory.[5] No "gold standard" metabolic measurement exists, and the conclusion is to use one type of equipment for all measurements in any given test.[6]

With the COSMED system, flow is measured at the mouth by a turbine flow meter, gas is sampled at the mouth, and oxygen and carbon dioxide fractions are measured in a portable unit designed to be carried by the subject. The portable unit is battery powered

to maintain electrical safety to the immersed subject. For this setup, subjects had to keep the sampling unit on the oronasal mask out of the water. The water-permeable gas sampling line between the mask and the portable unit was protected from splash by a piece of tubing slipped over it, and compressed air was blown through the tubing outside the sample line to remove water vapor. The portable unit and its battery were placed in a bucket on an adjustable stand above the water surface and near the subject's head. Measured values were stored in the memory of the portable unit and were either telemetered or downloaded later to a computer. Microsoft Excel was used for further processing.

Diver thermal dress was one of the experimental variables. When subjects wore swim suits or shorts and T-shirts ("PT gear"), they also wore wet suit booties to protect their feet from the foot cups. The wetsuits worn were 6 mm neoprene wet suits with booties, but for incremental exercise one wore a 3 mm suit, two wore 6.5 mm suits, and one wore a 7 mm suit, while for cadence testing one subject wore a 3 mm suit. The drysuits used were Viking Pro 1000 dry suits (Trelleborg Protective Products AB, Trelleborg, Sweden) which include bootlike footwear bonded to the legs. The NRV suits (Non-return hot water diving suits, Diving Unlimited International, San Diego, CA) were nominally 3/16" (5 mm) unicellular neoprene with a network of tubes inside the suits. The water system was hooked to a hose that pressurized all the tubing. Openings from the tubes brought water inside the suit, where it built up a back pressure if the leg valves were closed, as they were during this study. As subjects did not wear gloves, water could drain at the wrists. The suits included boots with thick soles.

PROCEDURES

Dry testing was conducted at a room temperature of about 23 °C (73 °F). Water temperature when subjects were without thermal protection was 28 ± 2 °C (82 ± 4 °F), and with wet, dry, or NRV suits it was 20 ± 2 °C (68 ± 4 °F). Water from an outdoor hose (temperature approximately 28 °C) was circulated in the NRV suits.

Graded Exercise, Constant Cadence of 60 rpm

Dry Testing

Dry testing on the upright ergometer began with unloaded pedaling, measured at 3.3 W, for four minutes. Each subsequent load was maintained for three minutes. The first applied load was 50 W, and loading continued in increments of 25 W to voluntary termination or a maximum of 250 W. Subjects were required to maintain 60 rpm.

Immersed Testing

The wet ergometer was mounted on a platform (the high stand) in the 15-foot deep test pool in a swimming configuration at approximately 30° from the horizontal. The ergometer level was adjusted as necessary to keep the subject's head and upper shoulders out of the water while the chest, legs, and bike box were submerged. An extra float, a board wrapped in closed-cell foam, was available as an aid in keeping the oronasal mask and its sample line out of the water. Some subjects held the float under their upper arms to help support their chests.

If subjects wished to do so, they used weight belts with the wet suits. Subjects in dry suits and NRV suits were tethered poolside in case a suit flooded and they needed assistance to exit the water.

Each subject warmed up with four minutes of pedaling at 60 rpm with no brake load, a condition that had been measured as 10 W at the shaft. As in the dry ergometry, each subsequent load was maintained for three minutes. The first applied load was 20 W, and loading continued in increments of 20 W to voluntary termination or a maximum of 240 W.

Effects of Cadence

For all dress except NRV suits, subjects in this phase used two power outputs, 30 and 50 W; with NRV suits, no brake loads were applied because subjects were unable to complete testing with added brake loads. Subjects first warmed up with unloaded pedaling at 60 rpm and then attempted to pedal at cadences of 45, 60, and 75 rpm ± 3 rpm for three minutes at each ergometer load. Except with NRV suits, ergometer settings were selected to factor out the relation of rotational speed, torque, and power. The current applied to the brake was that for the desired power at the applicable cadence, not for a chosen torque. However, with NRV suits without brake current, ergometer adjustments were not possible. The sequence of cadences was varied across subjects, but because subjects had difficulty sustaining 75 rpm in the water (particularly at 50 W), 75 rpm at 50 W was the final measurement in most , and 75 rpm at 30 W was selected as the second last measurement in many trials.

RESULTS

Dry Exercise: Oxygen Consumption as a Function of Ergometer Power

Peak oxygen consumptions measured on the dry ergometer ranged from 1470 to 4100 $mL \cdot min^{-1}$, with median value 2860 $mL \cdot min^{-1}$. The mean (standard error) of the regression slopes for oxygen consumptions as a function of power was 12.2 (0.3) $mL \cdot (min \cdot W)^{-1}$.

Graded Exercise, Constant Cadence of 60 rpm, Additional Power Independent of Setting

In-water cycling in all diver dress included a substantial extra power requirement, with the additional load different across individuals. The results in which additional power was apparently independent of workload are presented first. These results represent the entire record for some subjects, only the lowest shaft power setting for others, and a range of loads from lowest to intermediate for most subjects.

The median, minimum, and maximum values of additional power are shown in Figure 2, and the means and standard errors are given in Table 2. Variation in additional power, a range about 100% of the median value (Fig. 2), did not appear to be related to subject height, sex, or peak power achieved. The mean additional power requirement for PT gear and wet suit were not different (p>0.1 by unpaired t-test), and the average was considered to represent the power required to overcome water resistance.

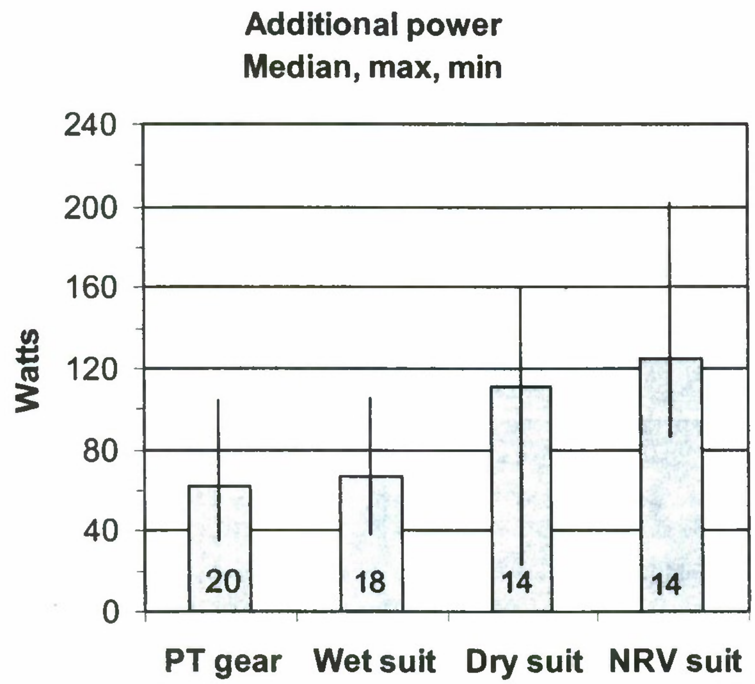

Figure 2. Additional power of cycling at 60 rpm in different diver dress. Solid bars give median values, and "whiskers" indicate ranges. Numerals on bars indicate numbers of subjects.

Table 2.

Additional power for cycling in the water, with additional power not a function of shaft power. Mean value, with standard error (SE) in parentheses.

60 rpm **Mean (SE)**	Additional power = Calculated – shaft power[W]	Increase over water resistance [W]
PT gear	64 (5)	
wet suit	69 (5)	
Average power to offset water resistance	**66 (10)**	
dry suit	104 (9)	38 (19)
NRV suit	126 (7)	60 (17)

Power-dependent Portion, Graded Exercise, Constant Cadence of 60 rpm

Many experiments included portions of the record when the additional power for pedaling in the water increased with ergometer power, either suddenly (Fig. 1, 100 W) or nearly linearly with ergometer setting (Fig. 3). These increases seemed to begin when surface waves appeared in the pool; although the additional power was not computed until after testing, many subjects stopped exercise soon after wave generation began.

The increase in additional power as a function of shaft power was estimated as the slope of the line segment from the last measurement deemed to be at steady additional power through the increasing values, and the mean and median values in each condition (Table 3) were calculated across all subjects who showed an increase. The increase with the wet suit did not differ from that with the PT gear ($p>0.5$).

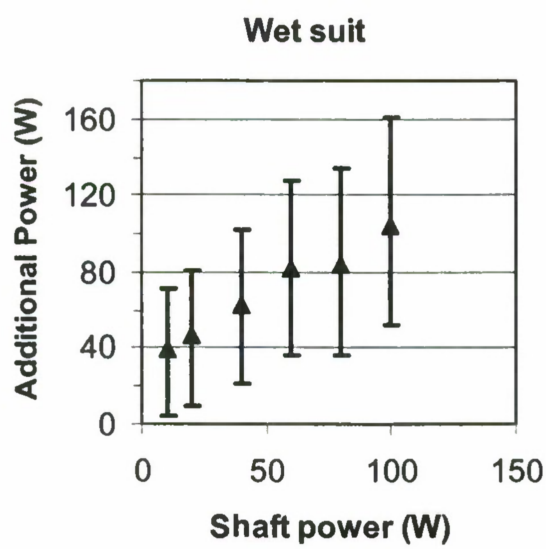

Figure 3. Example of increasing additional power with increasing shaft power, one subject. Triangles: Power calculated from one-minute averages of oxygen consumptions and the regression from dry ergometry (see **EXPERIMENTAL DESIGN AND ANALYSIS**). Error bars: 95% confidence intervals based on dry ergometer measurements.

Table 3.

Additional power for cycling in the water, with increase in power a function of added shaft power, linear estimation

60 rpm Linear increase	Mean slope (standard error) [W / 100 W shaft power]	Median slope [W / 100 W shaft power]
PT gear	94 (13)	75
wet suit	103 (16)	80
dry suit	151 (33)	126
NRV suit	163 (58)	106

Effects of Cadence

Even though the shaft torque was adjusted to keep the ergometer power requirement constant when cadence was adjusted, the extra power needed to move in the water was a strong function of cadence (median values, Fig. 4; means, Table 4). The additional power for 60 rpm is not identical to but reasonably agrees with the values shown in Figure 2 and Table 2. As indicated by the numbers of subjects associated with

the bars of Figure 4, not all subjects could complete all the cadence conditions; many stopped during or after a 75 rpm test.

Although the additional power appeared slightly higher at the 50 W setting than at the 30 W setting for both wet suit and dry suit (Fig. 4), two-way analyses of variance (ANOVA) with replication for effects of shaft power and cadence indicated that shaft power did not make a difference in additional power requirements in the water in PT gear or wet suit, nor did shaft power and cadence show an interactive effect. In those two forms of diver dress, cadence did have a strong effect on additional power ($p < 0.001$). Because few people completed all conditions while wearing dry suits and because shaft power changed with cadence for subjects in NRV suits, those forms of dress were not tested statistically.

Because the increase in power requirements were not linear with cadence, regression against cadence and comparison of slopes would not have been appropriate. Instead, the piecewise increments were compared. By two-way ANOVA without replication, average increments in additional power between 45 rpm and 60 rpm for PT gear, wet suit or dry suit and between 60 rpm and 75 rpm for PT gear and wet suit did not differ across shaft setting or diver dress. The increments in power requirements with increased cadence was greater at higher than lower cadence: for PT gear and wet suits combined, the mean increase was 66 W (SE 12 W) for a change from 45 rpm to 60 rpm but the mean increase was 41 W (SE 11 W) for a change from 60 rpm to 75 rpm, while for NRV suits, the mean increase was 110 W (SE 6) between 60 rpm and 75 rpm, but only 69 W (SE 8W) between 45 W and 60 W.

Table 4.

Effects of pedal cadence: Mean additional power relative to dry ergometry at 60 rpm, standard error (SE) in parentheses

Mean (S.E.)	30 W			50 W		
rpm	45	60	75	45	60	75
PT gear	38 (5)	82 (12)	144 (5)	46 (6)	86 (9)	148 (8)
Wet suit	23 (5)	62 (3)	124 (11)	38 (11)	78 (5)	146 (11)
Dry suit	59 (8)	107 (19)	112*	81 (14)	122 (5)	154*
NRV suit						
Shaft power	7.5 W	10 W	12.5 W			
Extra power	54 (11)	123 (15)	228 (9)			

*The values for the dry suit at 75 rpm represent single measurements.

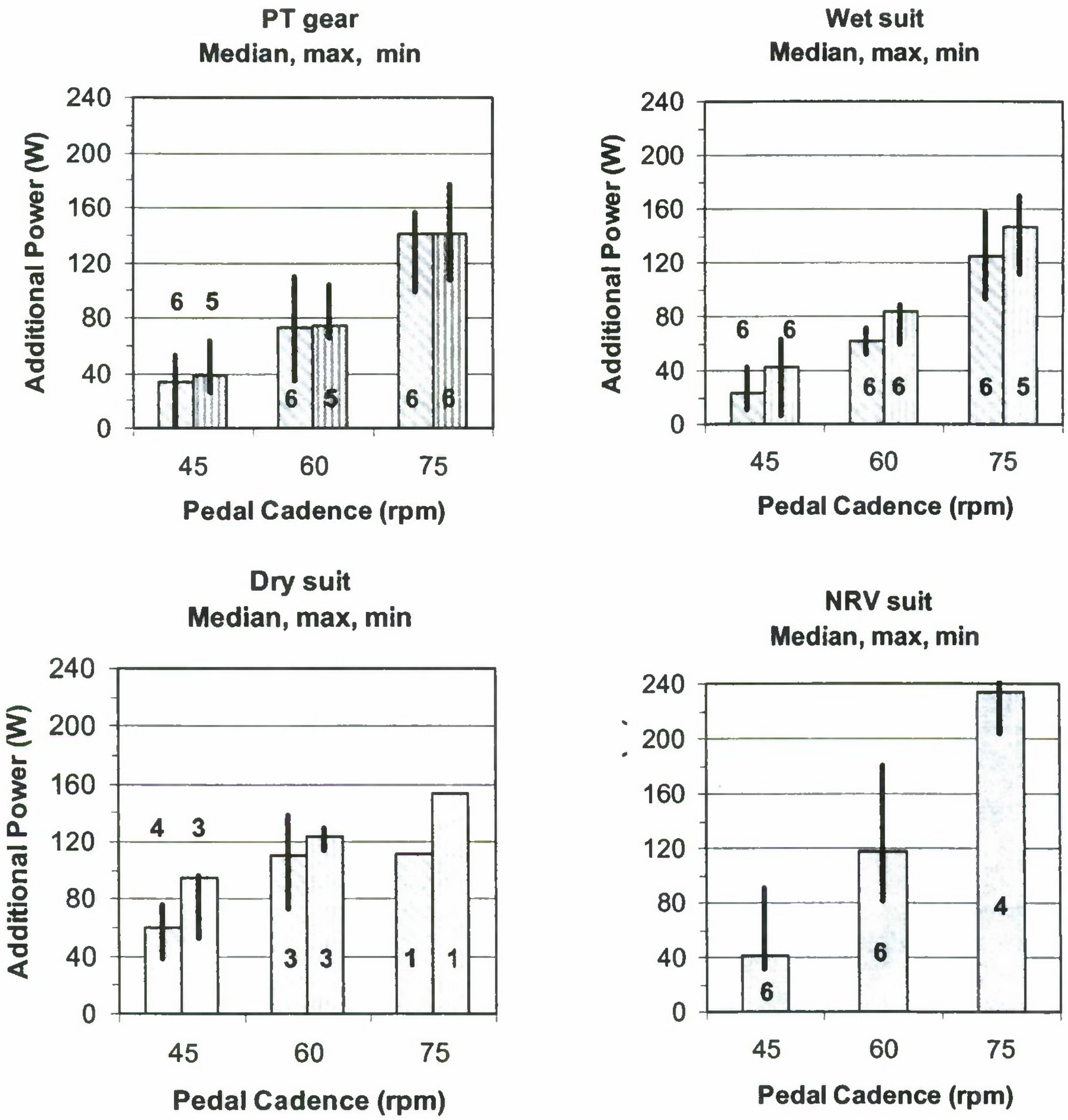

Figure 4. Effects of pedal cadence on additional power requirements. Bars are median values, whiskers join minimum to maximum, and numerals in boldface indicate numbers of subjects. Diagonal stripes: ergometer setting = 30 W. Vertical stripes: ergometer setting = 50 W. Values for 30 and 50 W at the same rpm do not differ statistically. Solid gray: no brake load, shaft power 7.5 W at 45 rpm, 10 W at 60 rpm, and 12.5 W at 75 rpm.

Decreasing cadences from 60 to 45 rpm reduced the additional power by an average of 42 W for subjects wearing PT gear, wet suit, or dry suit, while increasing cadences from 60 to 75 rpm increased the additional power by an average of 64 W for those in wet suits or PT gear (Fig. 3). For many subjects, pedaling at 75 rpm caused notable disturbance of the water surface. The mean decrease in additional power with the NRV suit was 69 W on decreasing the cadence from 60 to 45 rpm, and the mean increase was 105 W on increasing the cadence from 60 to 75 rpm.

DISCUSSION

During cycle ergometry in the water, the energy dissipated in the ergometer brake and in gear friction accounts for only part of the oxygen consumed. Oxygen is consumed also to accelerate water, to bend dive suits, and to overcome viscous drag, among other forms of power consumption. We assume that thermal regulation did not require much power output in these experiments.

While NEDU previously found approximately 50 W as the additional power requirement of in-water cycling,[1] other groups[2,3] have found approximately 25 W for the requirement, and we find closer to 60 W without thermal gear (Fig. 2). The difference among measurements is not related to posture or to type of ergometer. Although the tests reported by Almeling et al.[3] used an upright ergometer mechanically coupled to a dry ergometer, those reported by Thalmann, Sponholtz, and Lundgren[2] in Buffalo used nearly prone subjects and a hysteresis brake and gear box almost identical to those at NEDU.

The calculation of additional power of in-water cycling depends directly on the measurement of oxygen consumption. Methods differ among studies. While we measured breath by breath with a commercial system and the Buffalo study used breath-by-breath measurement with in-house software,[2] the previous NEDU study relied on the decrease in oxygen pressure in a rebreather breathing apparatus over 15 to 20 minutes of exercise,[1] and Almeling et al. collected expired gas in a spirometer and measured gas composition every 15 s.[3] In our measurements, the increase of oxygen consumption with increasing power output on the dry ergometer — 12.2 mL $\cdot$ $(\mathrm{min} \cdot \mathrm{W})^{-1}$ — is lower than the 13.8 mL $\cdot$ $(\mathrm{min} \cdot \mathrm{W})^{-1}$ derived from linear textbook data,[7] similar to the 12.6 mL $\cdot$ $(\mathrm{min} \cdot \mathrm{W})^{-1}$ reported by Thalmann et al. for dry ergometry in three subjects,[2] and higher than the 11.0 mL $\cdot$ $(\mathrm{min} \cdot \mathrm{W})^{-1}$ reported by Almeling et al. for dry ergometry.[3] Differences in oxygen consumption measurements among studies may reflect differences in technique, but they cannot explain the differences in calculated power requirements.

One likely difference in technique is that of securing subjects' feet to the pedals. In contrast to the large foot cups and neoprene booties used at NEDU, regular bicycle pedals with toe straps[2] over canvas shoes were used in Buffalo (personal

communication). The foot cups used at NEDU are large water scoops. Additionally, for some subjects the tops of borrowed wet suit booties were loose around the ankles, a looseness providing another source of drag. The tops of the booties were snugger against wet suit legs than against skin.

Another possible difference in the total power requirement among laboratories is in the system for securing the diver on the ergometer. For the measurements in Buffalo, divers were harnessed against a back plate that was fixed to the chamber walls.[2] Thus, almost all leg thrust was transmitted to the pedals. In the study by Almeling et al.,[3] subjects were seated on an upright ergometer, presumably with either sufficient weight or a seat belt to hold them to the seat. However, for our and for the previous NEDU measurements, subjects leaned against shoulder horns, supports that rocked laterally, and had no constraints for motion of the torso. Some of the leg thrust caused vertical and rocking motions of the body. Such motion of the torso displaced and accelerated large volumes of water, and perhaps contributed to the wide variation in additional work among subjects (Fig. 2). Vertical body motion of increasing amplitude with increasing shaft power may be the main source of the increases in additional work with shaft load for some subjects. Some subjects lifted their shoulders and upper backs out of the water when shaft power was high and thus used energy to support themselves. Even with firm attachment of subjects, Thalmann et al. reported a slight increase in slope with shaft load, an increase of 0.05 L min^{-1} per 100 W as compared to the slope in dry exercise, or an additional 4 W per 100 W,[2] but the changes with shaft power reported here are approximately 20-fold higher (Table 3).

NEDU had previously approximated values for extra power requirements in water plus suit as being about 85 W for a wet suit or dry suit and about 110 W for a hot water suit,[1] while we calculated about 70 W with a wet suit, 110 W with a dry suit, and 120 W with an NRV suit when added power was independent of shaft power (Fig. 2). Our numbers do not truly disagree with the earlier NEDU studies; those values, based on very few ergometer settings, had large uncertainty and could not distinguish changes dependent on or independent of shaft power. We also found a wide range of values among subjects (Fig. 2).

Neoprene wet suits did not impose a load in addition to that of the water, but the dry suits and NRV suits charged with water did. Some of the additional power relative to that for PT gear or wet suit (Table 2) may be consumed by the drag of boots rather than booties through the water. Not only was the constant extra power in those garments higher than that for PT gear, but also the increase was steeper if the additional power became a function of shaft power. If the increase in extra power with shaft power is caused by a torso's pumping action as the subject "steps harder" on the pedals, the greater increase with dry suit or NRV suit than with PT gear or wet suit (Table 3) may be caused in part by the greater difficulty of moving in those suits.

CADENCE

When testing cadence, we measured somewhat different values for extra power at 60 rpm from those we saw during incremental exercise (Tables 2 and 4). Because subjects generally performed either an incremental test or a test of cadence in any one form of dress, the two tables include results from different subjects. Further, variation of extra power with shaft load could not easily be monitored during the tests of cadence. The differences between Table 2 and Table 4 for 60 rpm may have resulted from greater body movement in the cadence measurements than in the incremental tests or simply from variability among subjects.

Because the ergometers commonly used in NEDU testing have feedback circuits to adjust the brakes for constant power requirements if cadence changes, effects of pedal cadence have often been dismissed. The results from our experiments indicate that cadence exerts an important effect on the *additional* power of pedaling in the water, even without thermal gear.

The power expended in turning the ergometer includes that related to torque, that to overcoming viscous and form drag, and that to centripetal acceleration of extra mass at the feet.

Although shaft torque does not change with diver dress, torque to flex knees, hips, and ankles of a suit may. (One would not expect extra torque for divers in PT gear.) The torque to flex the suit will be independent of cadence, but power (P) related to torque (T) increases linearly with rotational speed:

$$P_{(torque)} = T \cdot \omega,$$

where ω is rotational velocity [radians $\cdot$ s^{-1}]. That is,

$$\omega = (\text{cadence [rpm]}) / (60[\text{s/min}] \cdot 2 \cdot \pi \, [\text{radians/rotation}]).$$

Form drag also may differ with diver dress. Power related to form drag increases with the drag coefficient and frontal area of the object, and with the cube of velocity:

$$P_{(drag)} = 0.5 \cdot \rho \cdot v^3 \cdot A \cdot C_d,$$

where ρ is the water density; v is linear velocity, here of the legs, feet, and, for some subjects, torso; A is the frontal area of the legs, foot cups, and for some subjects the chest; and C_d is drag coefficient of the legs, foot cups, and sometimes chest. C_d is independent of pedal cadence. A varies with cadence only if a change in cadence stimulates a change in overall body motion. Similarly, A may vary with shaft power if added power induces increased body sway. Although v varies for different parts of the

leg and different times in the rotational cycle, it is approximately proportional to cadence. Thus, $P_{(drag)}$ increases with cadence raised to the third power.

Centripetal force to keep extra mass in the feet traveling in a circle may vary with diver dress. Power related to the centripetal force, like that to overcome form drag, increases with the cube of cadence:

$$P_{(centripetal)} = m \cdot \omega^3 \cdot r^2 = \mathrm{I} \cdot \omega^3,$$

where m is extra mass (e.g., water in the NRV boots); r is the radius of the circle traced by the pedals, approximately the crank length; and I is the moment of inertia.

If torque causes the dominant extra power requirement at elevated cadence to bend the suit, the torque for each form of dress could be estimated by dividing power by cadence to yield a consistent value at all cadences. If, however, drag or centripetal forces dominate, division by the third power of cadence should yield nearly a single value for each diver dress, the sum of numbers proportional to $A \cdot C_d$ and I.

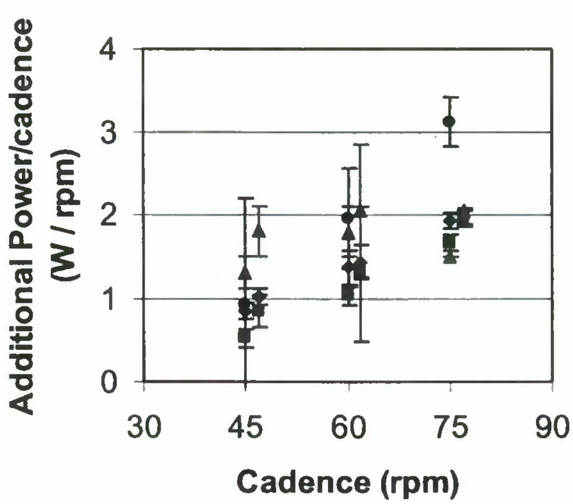

Figure 5. Mean additional power to pedal in the water at different cadence, divided by cadence. A value constant across cadence would indicate an additional torque. Values when shaft power was 50 W are offset slightly to the right of those with shaft power of 30 W. Bars represent standard error. Symbols: blue diamond, PT gear; red square, wet suit; green triangle, dry suit; and black circle, NRV suit.

Division of additional power by cadence did not yield a consistent value, except perhaps for subjects in dry suits (Fig. 5). Power must be required to flex the suits, but that power was generally swamped by the other requirements; power used cycling in a wet suit was similar to or lower than that used in PT gear (Figs. 2, 4; Tables 2, 4). For subjects in dry suits, torque to flex the suits may have been the dominant sink for additional power, but because the additional power requirements were so high, we were able to collect relatively few data for varied cadence in dry suits (Fig. 4), and only one of the subjects was able to complete all three cadences at either shaft power setting.

Division by the third power of cadence brought values for each form of diver dress into concordance across cadence (Fig. 6), again except for subjects in dry suits. The average values, weighted by numbers of subjects, are $3.9 \cdot 10^{-4}$, $3.3 \cdot 10^{-4}$, and $5.1 \cdot 10^{-4}$ W $\cdot$ rpm^{-3} for PT gear, wet suit, and NRV suit, respectively. The values for PT gear and wet suit are most likely proportional to form drag, although the mass of water in the foot cups also must be accelerated into circular motion in those forms of diver dress. As has been discussed, exposed tops of wet suit booties may be responsible for greater drag in those wearing PT gear than in those in wet suits, or the populations may have been sufficiently different to create the small difference in drag through different size or different technique.

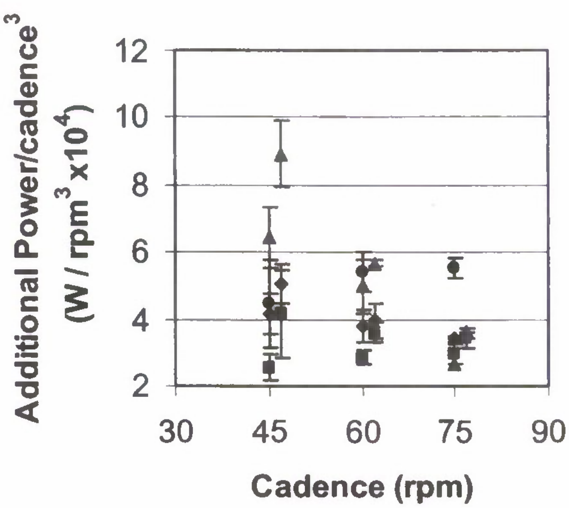

Figure 6. Mean additional power to pedal in the water at different cadence, divided by the third power of cadence. A value constant across cadence suggests additional drag or moment of inertia. Symbols are as in Figure 4.

The extra power for cycling in a dry suit is offset from that for cycling in PT gear by constant power independent of pedal cadence, about 23 W with 30 W shaft power and about 44 W for 50 W shaft power. A possible power requirement independent of cadence is that to maintain posture in the absence of the flotation of neoprene but with the compression of the suit.

NRV suits require extra power above that for wet suits, extra power that is also a function of the cube of cadence. Although NRV suits are bulkier than wet suits, the frontal surface area of the legs is not large enough to explain the 40% increase in drag relative to that with wet suit. The heels of the boots increase drag at times during a pedal rotation, but a major component of the difference between wet suits and NRV suits is probably the mass of water inside the feet and legs, a mass that has to be maintained in circular motion — in other words, increased moment of inertia. While tension in the pedal shaft provides the force, the kinetic energy has to be supplied by the cyclist through added oxygen consumption.

CONCLUSIONS

As measured by oxygen consumption, subjects using the in-water cycle ergometers at NEDU require substantially more power than that consumed by the brakes, and more additional power than that measured at other institutions. The large foot cups and relatively weak stabilization of subjects on the ergometers are the likely sources of the disparity across laboratories.

With the NEDU apparatus, even at fixed and well-characterized ergometer power the variability of physiological load among subjects is high. For example, with no thermal dress, in-water cycling may increase the ergometer setting by 38 W for one subject and by 100 W for another at low shaft power settings — and by even greater amounts as pedal torque is increased, if the subject manifests added body motion. For subjects wearing dry suits, the range of additional power was approximately 50 W to 160 W at low shaft power. Subject pedaling posture probably is important in controlling the oxygen consumption.

The measurements at different cadences indicate that form drag or perhaps centripetal acceleration of water causes the principal additional power requirement for subjects in all diver dress measured here, that dry suits include a constant power addition, and that acceleration of the water inside the feet and legs of the NRV suits is also a significant power sink. Additional torque does not appear to be significant. Wet suits do not increase the power requirement over that for cycling in the water in PT gear with wet suit booties.

Pedal cadence is extremely important in determining the total power expended, even after the ergometer brake is adjusted to compensate. Because power to overcome form

power of rotational speed, subjects must work much harder to cycle if they increase cadence. For the NRV suit with its large mass of additional water, the additional power becomes untenable at all but minimal shaft power.

Ergometers are used during NEDU dive profiles to increase oxygen consumption. The current study shows that they may do this too well. Even when the power required to spin the brake is well determined, the power required to overcome drag may dominate, and the additional power requirements differ among subjects. Knowledge of the ergometer setting and the mean or median additional load for the form of diver dress will provide at best a first approximation of the oxygen consumption. If uniform oxygen consumption across subjects is needed, oxygen consumption must be measured.

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